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Temporal variation of soil gas compositions for earthquake surveillance in Taiwan

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HIGHLIGHTS

► Variations of soil–gases composition is studied at two different faults of Taiwan.
► Tectonic based model for earthquake forecasting in Taiwan was proposed and tested.
► Selection criteria to identify threshold earthquakes have been defined.
► Stress/strain transmission for earthquake may be hindered by tectonic settings.

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ABSTRACT

The present study is proposed to investigate temporal variations of soil–gas composition in the vicinity of different fault zones in Taiwan. To carry out the investigations, variations of soil–gases compositions were measured at continuous earthquake monitoring stations along Hsincheng and Hsinhua faults in Hsinchu and Tainan areas, respectively. Before selecting a monitoring site, the occurrence of deeper gas emanation was investigated by the soil–gas surveys and followed by continuous monitoring of some selected sites with respect to tectonic activity to check the sensitivity of the sites. Based on the results of long term geochemical monitoring at the established monitoring stations we can divide the studied area in two different tectonic zones. We proposed tectonic based model for earthquake forecasting in Taiwan and tested it for some big earthquakes occurred during observation period i.e. 2009–2010. Based on the anomalous signatures from particular monitoring stations we are in a state to identify the area for impending earthquakes of magnitude ≥ 5 and we have tested it for some earthquakes which rocked the country during that period. It can be concluded from above results that the stress/strain transmission for a particular earthquake is hindered by different tectonic settings of the region under study.

1. Introduction

Soil–gas measurement has been identified as a potential technique in scientific methodology used to study active faults and earthquake precursory signals. Measurements of soil–gases have attracted considerable attention over the past several years due to its relationship with the seismicity. Information carried by various gases (viz. radon, helium and carrier gases (viz.) carbon dioxide, nitrogen, methane etc.) with different origins in soil have been used to trace various fault systems (Baubron et al., 2001; Fu et al., 2005; Guerra and Lombardi, 2001; King et al., 1993; Walia et al., 2009a, 2010) and earthquake precursory studies (Kristiansson and Malmqvist, 1982; Segovia et al., 1989; Kumar et al., 2009; Walia et al., 2005; Woith and Pekdeger, 1992; Yang et al., 2006). Outgassing process of gases in soil at a given locale is apparently controlled by the interaction of geological, pedologic, climatic and metrological factors.

Radon concentration variations have been established as a major contributor for seismic surveillance for few decades. While other gases have also been considered as possible earthquake precursors, however, bulk of reports in the scientific literature are focused on radon. It has been accepted that radon and other gases can escape towards the surface by diffusion, advection and convection and also by rising fluids or carrier gases. Diffusion is the simplest mechanism, but owing to its short half-life, radon cannot travel more than a few meters. The second mechanism, the advection mechanism, is mostly dominated in fault zones and fractured systems and convection can occur when a sufficient thermal gradient is available within the soil, depending on many

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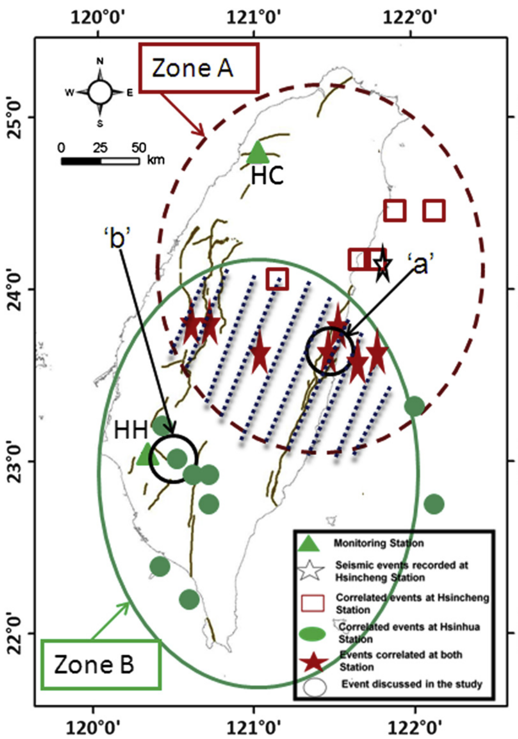

Fig. 1. Proposed tectonic based model for Taiwan and distribution of events recorded at monitoring stations along Hsincheng (HC) and Hsinhua (HH) faults.

local parameters, such as viscosity, porosity, permeability and so on. The transport by means of gas carrier (Etiope and Martinelli, 2002; Yang et al., 2003, 2011) is particularly important inside a volcanic edifice, where gases, such as, CO_2, H_2O, SO_2 and H_2S etc. are abundantly present and can be good carriers of radon, reaching the surface at very high rates.

The skepticism, that accompany the earthquake precursory phenomena, may be due to non-existence of a universal model and has been a challenge for quite some time which created lots of interest in scientific community to solve this problem. Some models/empirical relations have been proposed in the past relating radon anomalies and seismic parameters, such as, earthquake magnitude and epicentral distance etc. (Toutain and Baubron, 1999; Virk, 1996; Walia et al., 2003). Such relations can be classified both theoretically and empirically (Etiope et al., 1997: Walia et al., 2005). Most of the proposed relationships or models are under debate; however, still in agreement that episodic crustal stress/strain is a possible source mechanism for precursory signals.

Taiwan is a product of the arc-continent collision between Philippine Sea plate and Eurasian plate which makes it a region of high seismicity. In the southern area of island, the Eurasian plate is subducting under the Philippine Sea plate while in the northern part of the island, the Philippine Sea plate bounded by the Ryukyu trench is subducting beneath the Eurasian plate. Behind the Ryukyu trench, the spreading Okinawa trough has developed. The northern part of Taiwan Island is located at the western extrapolation of the Okinawa trough. These collisions are generally considered to be the main source of tectonic stress in the region and are, thus densely faulted and seismically active.

The present study is aimed to test proposed tectonic setting based model (Walia et al., 2009b) from data obtained at earthquake monitoring stations along Hsincheng fault (HC) in Hsinchu area and Hsinhua fault (HH) in Tainan area using soil gas method during observation period of year 2009–2010. These two monitoring stations lie in the north and south part of Taiwan, respectively. Detailed geology and tectonic features of the monitoring stations are reported elsewhere (Walia et al., 2009b).

1.1. Continuous monitoring station setup

To carry out the investigations, temporal soil–gases compositional variations were measured regularly from a PVC cased dug hole about 2 m of depth at continuous earthquake monitoring stations using RTM2100 (SARAD) for radon and thoron measurement following the procedure as described in Walia et al. (2009b). Seismic parameters (viz. earthquake parameters, intensity at monitoring station etc.) and rainfall and data were obtained from Central Weather Bureau of Taiwan (www.cwb.gov.tw).

2. Results and discussion

Based on previous years (i.e 2006–2008) long term geochemical monitoring results at the established earthquake monitoring stations HC and HH, we proposed and published a tectonic based model (Walia et al., 2009b). According to the model HC and HH monitoring stations recorded different precursory signals for impending earthquake that happened in different tectonic settings/zones of Taiwan (Fig. 1). It was observed that variations in soil gas at HC are disturbed by the stress variation due to tectonic activities in Zone A i.e. along Okinawa Trough and Ryukyu Trough which are located in north and central eastern part of Taiwan, respectively, in addition to local earthquakes within periphery of about 50 kms from the monitoring station. Whereas in the case of HH, soil–gas variations are observed to be due to tectonic activities in Zone B i.e along the Luzon Arc and subduction of Eurasian plate in southern part of Taiwan. Hence, it implies that HH monitoring station shows precursory signals for earthquakes occurring south or south eastern part of Taiwan, whereas, for HH most of soil–gas variation precursory signals are recorded for the earthquakes that occurred north or north-eastern part of Taiwan. However, both the monitoring stations have some common overlapping zone (shaded part in Fig. 1), indicative of the fact that the earthquakes that happen to be in this region might have precursory signals in both the monitoring stations.

In earthquake prediction research it is extremely important to estimate the size and shape of the earthquake preparation zone. We calculated effective/strain radius (D in kms) for earthquake preparation zone using Dobrovolsky (1979) formula:

$$D = 10^{0.43M}$$

where M is magnitude of the earthquake.

Taiwan is one of the most active seismic regions of the world with an average of about 20,000 earthquakes occurring every year in or around Taiwan as reported by Central Weather Bureau of Taiwan (www.cwb.gov.tw). Therefore, it is essential to define selection criteria to identify threshold earthquakes for this study. Based on the anomalous signatures from particular monitoring stations we are in a state to identify the area for impending earthquakes of magnitude ≥ 5. For selection criteria, earthquakes having local intensity ≥ 1 at the monitoring stations with epicentral distance $(R) < 150$ kms having D/R ratio ≥ 1 with focal depth < 40 kms are considered.

Soil–gas variation and its correlation with different seismic events observed at both monitoring stations for the observation period are plotted in Figs. 2 and 3. Long term observations show that both the monitoring stations have different characteristics and show different type of anomaly pattern. HH monitoring station shows diurnal variation whereas these types of diurnal variation are not noticed for HC monitoring station. Different characteristics

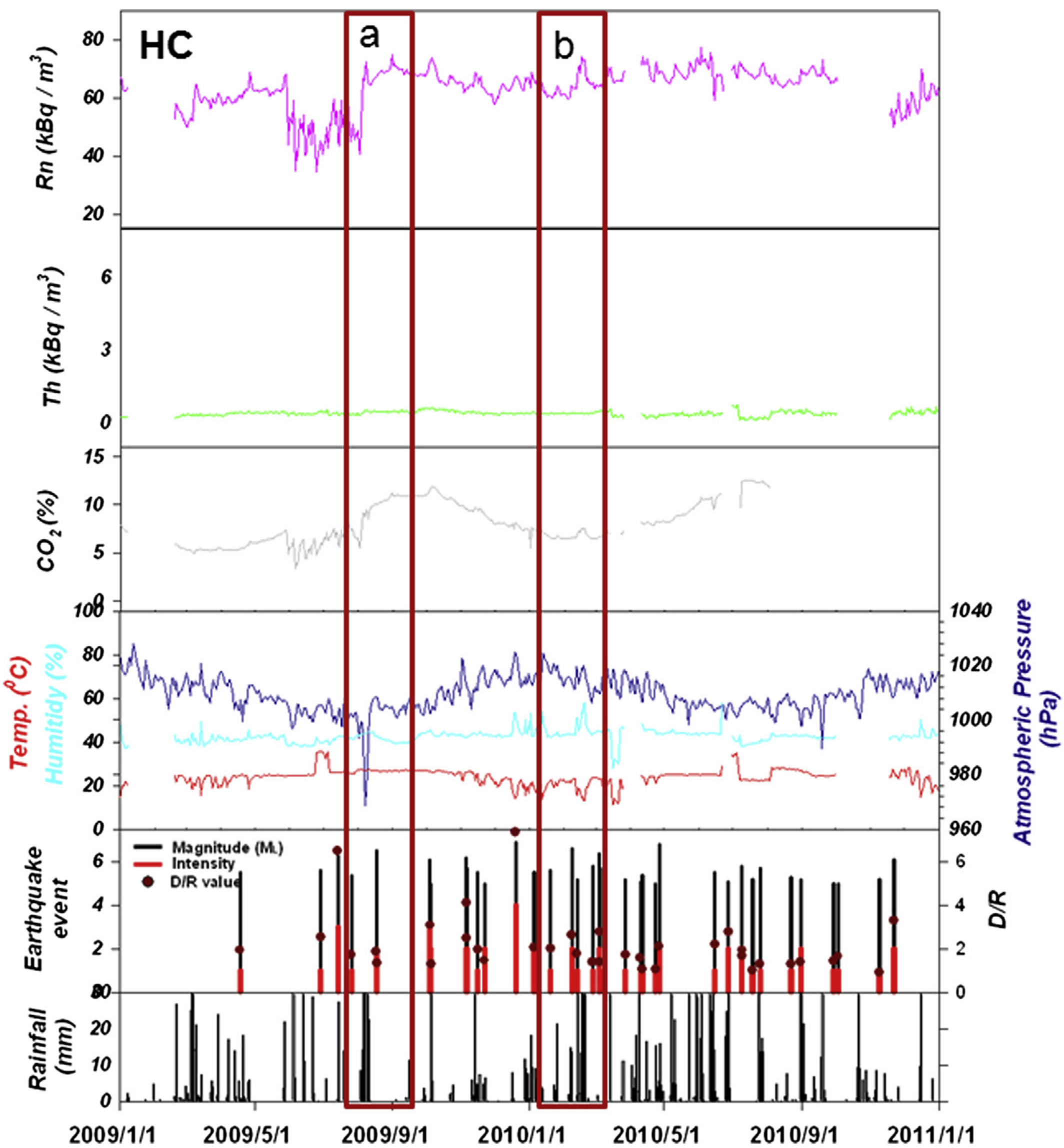

Fig. 2. Daily variations of radon, thoron, carbon dioxide and rainfall at Hsincheng monitoring station and their correlation with all the earthquakes with magnitude ≥5 during the observation period.

of two stations may be attributed to local geological conditions, effect of different meteorological parameters (i.e. pressure, temperature etc.) and water table. In case of HH monitoring station water table is found to be at shallower depth in the area (Walia et al., 2010). Diurnal variations in HH monitoring station data may be due to meteorological parameters where these have shown a better correlation with a correlation coefficient of −0.37 and 0.21 for pressure and temperature, whereas in case of HC it is 0.09 and −0.12, respectively. In general, non occurrence of diurnal variation of soil–gas radon concentration at HH station is identified as an anomaly (Fig. 3), whereas, in case of HC station, spikes are identified as anomalies.

During the observation period of 2009 and 2010, 25 and 34 earthquakes of magnitude ≥5 were recorded for respective years. However, out these 59 earthquakes only 22 fit well under the defined selection criteria as shown in Fig. 1 and tested for the proposed model. Those, which did not fit in our criteria, were either deep focus or far distant earthquakes. Most of the recorded earthquakes fitted well in the proposed model expect one earthquake of magnitude 5.3 (in Fig. 1 represented by empty star). In addition, two earthquakes lie in the proposed common zone of the model but have not shown precursory signals at both the stations (Fig. 1). In the present study two major earthquakes are chosen to test the proposed model, i.e marked as ‘a’ and ‘b’ in Figs. 2 and 3, respectively and will be discussed accordingly.

To test the proposed model, we first consider the earthquake that occurred in Eastern Taiwan on October 4th, 2009 having magnitude of 6.1 (M_L) with focal depth of 29.2 kms and followed by number of aftershocks with major aftershock of magnitude 4.9. The epicenter of this event was found to be in the common zone (shaded zone in Fig. 1). The epicentral distances of this seismic event were found to be 135 kms for HC and 142 kms for HH, respectively. Local intensity was found to be 3 and $D/R > 1$ at HC, whereas in case of HH monitoring station these values are found to be 2 and 1, respectively. On the expected ground, soil–gas variations at both monitoring stations have shown precursory signal for this earthquake (Fig. 4). It was noticed that at the HH station the values started increasing instead of showing their normal diurnal

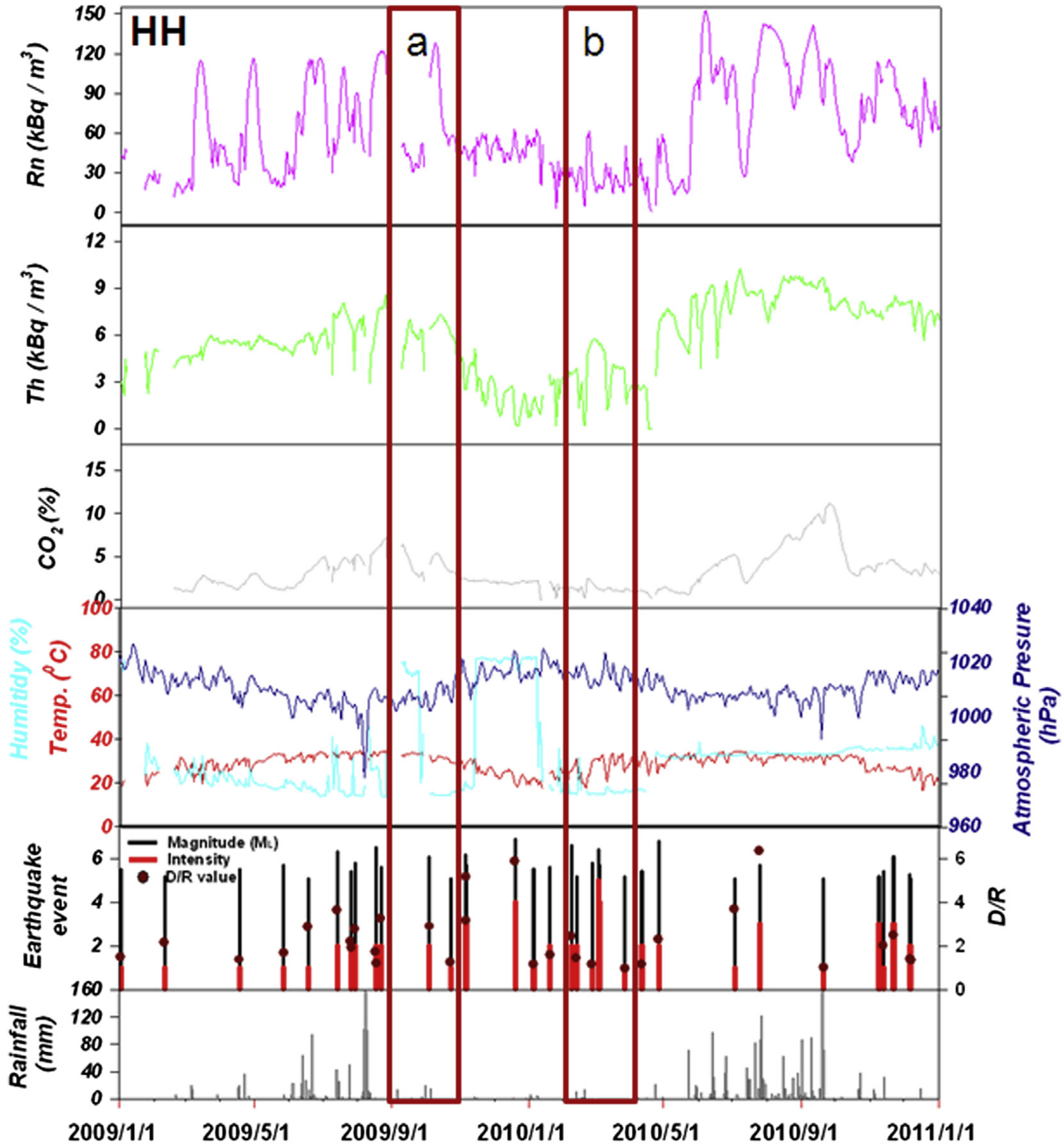

Fig. 3. Daily variations of radon, thoron, carbon dioxide and rainfall at Hsinhua monitoring station and their correlation with the earthquakes with magnitude ≥5 during the observation period.

variation after 24th of Sept., 2009 and continued to rise even after the earthquake. Although we lost about two days data (i.e dated 1st and 2nd Sept) due to power failure but rising trend in radon concentration is considered to be a precursory signal (Fig. 4). Similarly, precursory signals were also found at HC monitoring station. Radon concentration started increasing on 1st of October (i.e 3 days before the event) and reached the maxima on 5th October.

Another good example to test the proposed model is the earthquake occurred on March 4th, 2010 in Southern Taiwan with magnitude of 6.4 (M_L) and depth of 22.6 kms. This earthquake lies in zone B of the proposed model. Monitoring station HH having the local intensity 6 for this earthquake with D/R value of >4, have shown precursory signals (Fig. 1). Radon concentration at HH station started increasing with maxima recorded on 23rd February, 2010 about 8 days before the event. The radon concentration reached normal values on 26th Feb., about 5 days before the event (Fig. 5). The HC monitoring station present in north Taiwan did not show precursory signals for the above said earthquake. Although an anomaly was recorded at station between 13th Feb. and 18th Feb., but these anomaly patterns may be attributed to nearby local earthquake/s.

3. Conclusions

It can be concluded from the above results that the stress/strain transmission for a particular earthquake is hindered by different tectonic settings of the region under study. Results from our two monitoring stations of Taiwan are indicative of this fact. Hence, if anomaly/s were detected at one geochemical monitoring station and none at the other station, it can be concluded that pre-earthquake strain accumulation in one zone was not transferred to other zone and this may be the cause of missing precursory signals. On the other hand, if the impending earthquake occurred in common zone we expect to have anomaly in both monitoring stations. To correlate any impending earthquake with geochemical monitoring it is essential to identify the earthquake preparation zone. The tectonic based model fitted well for some earthquakes of magnitude ≥5. Therefore to have good monitoring results and to have useful data with respect to temporal variations of pre-

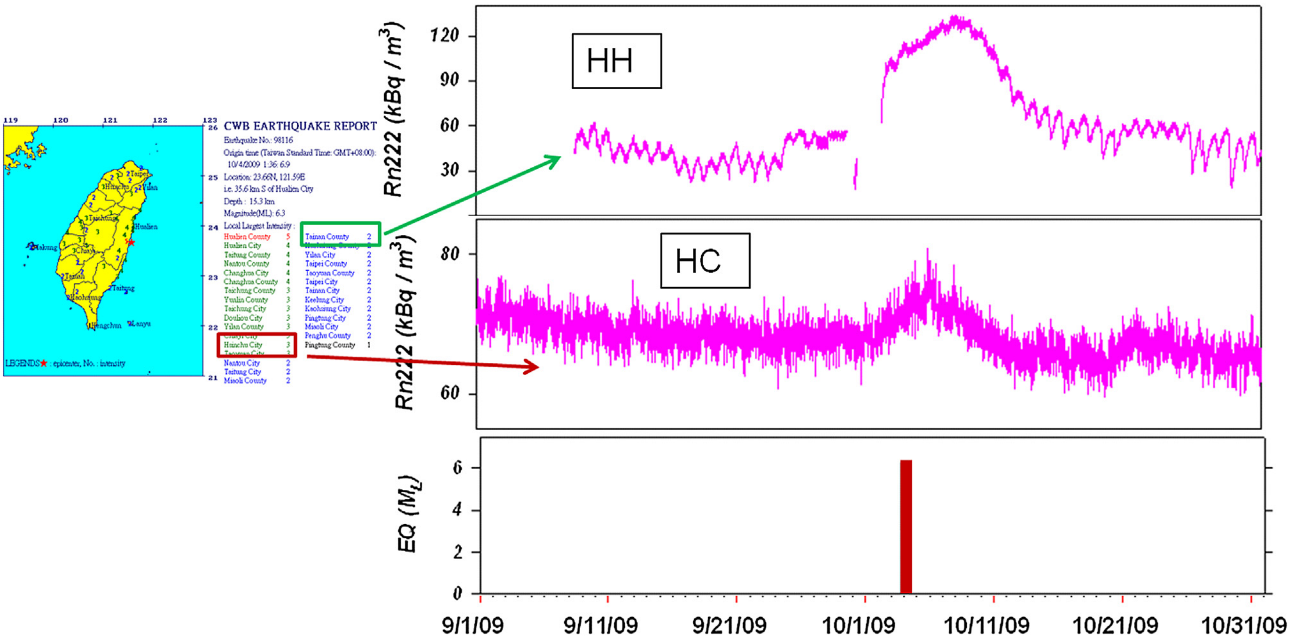

Fig. 4. Precursory signals for October 4, 2009 earthquake at both the monitoring stations.

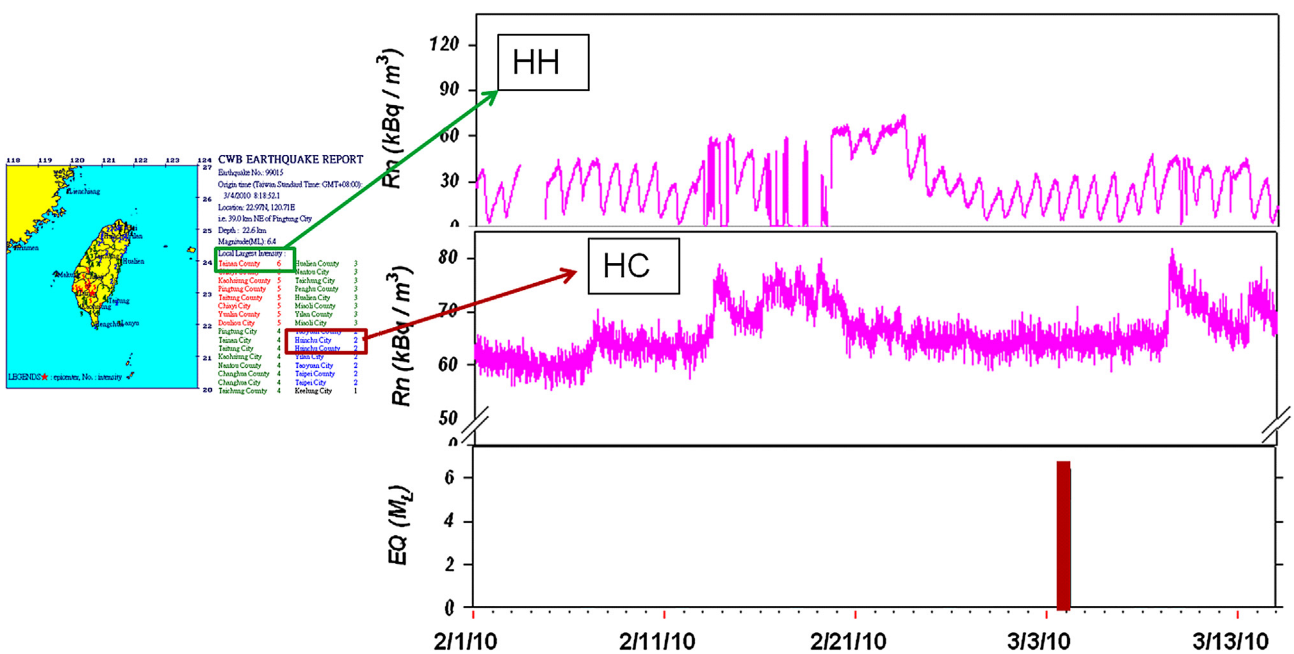

Fig. 5. Precursory signals for March 4, 2010 earthquake at both the monitoring stations.

earthquake signals, number of monitoring stations should be established to cover all quadrant characteristics of precursors as well as to overcome hindrance of pre-earthquake strain transfer in tectonically different zones.

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